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Study of Target Penetration Prediction by High Speed and Ultra High Speed Ballistic Impact

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AIR PROVING GROUND CENTER
Air Force Systems Command
United States Air Force
Eglin Air Force Base, Florida

AIR PROVING GROUND CENTER

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FOREWORD

This report was prepared under Air Force Contract Number AF 08(635)-2155, "Study of Target Penetration Prediction By High Speed and Ultra High Speed Ballistic Impact". Work was administered under the direction of APGC (PGWR), Eglin Air Force Base, Florida.

Catalog cards may be found at the back of this document.

ABSTRACT

Following a general discussion of material properties under impulsive loading some justification is given for using available static and quasi-static material properties for correlation with hypervelocity impact cratering. A preliminary analysis of the correlation between depth of penetration and ten independent variables has been performed on the digital computer, but sufficient time for a complete interpretation of the results was not available during this report period. However, a glance at multiple correlation coefficients indicates quite a strong dependence of crater depth upon the tensile yield strength of the target relative to some of the other independent variables. About 96% of the variance in crater depth may be explained by variations in the ten independent variables chosen for this first analysis.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Morrill E. Marston

MORRILL E. MARSTON
Colonel, USAF
Deputy for Aerospace

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LIST OF SYMBOLS

P_c	crater depth measured from original target surface
D_c	crater diameter at original target surface
D_p	projectile diameter
ρ	density
v	impact velocity
c	dilatational wave velocity in given material
m	projectile mass
T	target temperature
V	volume
Y	yield point
U	ultimate strength (tensile)

SUBSCRIPTS

t	target
p	projectile
c	crater
o	STP conditions or arbitrary reference point

INTRODUCTION

The purpose of this study is to gather and assemble existing data on ballistic impact and on material failure, especially at high impact velocities or large loading - to establish the relative importance of factors such as projectile velocity, mass, sectional density, projectile/target contact areas, etc., and to use this information to deduce the mathematical relationships of critical factors as the target structure responds to impact and is penetrated.

Existing experimental data relative to ballistic impact at high velocities are being evaluated on a statistical basis through the use of an RPC 4000 digital computer. The general form of the statistical approach was outlined in the first progress report and will be further discussed in this report. It is anticipated that this statistical study will result in a mathematical model which will be suitable for engineering purposes in predicting target behavior under a given set of design conditions.

Different velocity regimes, such as outlined by Hopkins and Kolsky[1], will be studied with the view in mind of extending the resulting solutions to higher impact velocities than those which have been considered to date.

If possible, separate mathematical models will be considered for the following three types of target behavior:

1. Penetration (dependent design variable - depth of crater)
2. Penetration - Plus - Scabbing (dependent design variable - target thickness)
3. Perforation (dependent design variable - target thickness)

In addition, dependent variables involving crater volume and diameter are being considered.

The following parameters are presently being included as independent variables in each of the three cases:

A. Projectile diameter, volume, and normal impact velocity
B. Target temperature
C. The following projectile and target material properties: density, longitudinal wave velocity, bulk wave velocity, yield strength, shear strength, ultimate strength, per cent elongation at fracture, Young's modulus, and Brinell hardness.

In addition, combinations of these dependent variables such as projectile kinetic energy ($\frac{1}{2}$ m v^2) and projectile mass (ρ V) form new dependent variables.

Progress to date on the penetration model is reported herein. Existing experimental data related to the condition of target scabbing under high speed impact appears rather limited. A statistical study of scabbing from a design standpoint is further complicated by the need for a standard point of reference, such as the target thickness at which scabbing begins to occur for a given set of impact conditions and materials. However, it is intended that at least an estimate of the design aspects of target behavior with regard to scabbing will be attempted.

Slightly more data exists concerning target perforation at least for relatively thin targets. Again, the problem of the dividing line between penetration-plus-scabbing and perforation becomes somewhat vague. However, it seems reasonable to define the onset of perforation as the impact velocity or target thickness at which kinetic energy is carried away from the back of the target in the direction of impact.

GENERAL ASPECTS OF TARGET BEHAVIOR

From an engineering point of view the behavior of a target under ballistic impact can be separated into the three categories -- penetration, penetration-plus-scabbing, and perforation. Of course, the scabbing phenomenon is just one example of tensile fracture resulting from stress wave interference. Targets are also subject to shear fracture, particularly in regions of high pressure; but in both cases, the cause of fracture can usually be attributed to transient stress conditions that develop as a result of stress wave interferences. It is also noted that some materials (steels) exhibit a time delay before the initiation of plastic flow which tends to produce a more brittle type of fracture. Some other metals (aluminum, brass) do not show time-dependent plastic flow properties. While there are a multiplicity of factors that can affect target behavior, for a given set of impact conditions and materials the factors that determine which of the three behavior categories will result are principally the target thickness and whether the target material behaves substantially as a brittle or ductile material.

The problem of predicting material resistance to high speed impact is a difficult one largely because of the fact that the question of ductility versus brittleness is a relative and variable one. While some materials are more brittle or ductile than others for a given set of conditions, a given material may behave as a brittle or ductile material depending on such conditions as temperature, strain rate and pressure. In general, a given material tends to become less ductile at higher strain rates and lower temperatures and more ductile under high pressures. At least for ferrous metals, there is a definite transition temperature range between ductile and brittle behavior, and rapid strain rates tend to raise this transition temperature so that decidedly brittle behavior occurs at higher temperatures when subjected to higher strain rates. This transition range is not generally found in the case of non-ferrous metals. Materials under high pressure tend to be more susceptible to shear fracturing, although other effects (time delay for yielding, high strain rates, low temperatures, etc.) may cause a more brittle (tensile) fracturing under hypervelocity impact.

Metal targets tend to pass from "penetration" to "penetration-plus-scabbing" to "perforation" types of behavior as the target thickness decreases. However, the mechanism of these different behaviors, and their transition from one to the other, are quite different in brittle and ductile targets.

A relatively thick ductile target will, in general, undergo a more or less hemispherical crater formation under hypervelocity ballistic impact; at least for impact velocities not greatly exceeding the dilatational wave velocity of the target material. In this case, the depth of penetration is the important design variable and is dependent on several variables as previously listed. A brittle metal target, which is too thick to be perforated, will be penetrated as the ductile target (similar crater formed), although the mechanism of cavity formation is somewhat different in that the brittle target may tend to spall in the vicinity of the crater rim and is more susceptible to scabbing fracture. Since the energy necessary to propagate a crack is very small, it seems reasonable that spall may affect the depth of penetration only as a secondary effect. For example, the spalled away material may give a larger solid angle for the low resistance ejection of material from the growing crater. In relatively thick targets of both brittle and ductile materials, it appears that the resulting depth of penetration is the primary design factor of interest.

Although scabbing is more critical in brittle targets, it may occur in either brittle or ductile materials and may result in a small tensile crack or a complete breakdown of the target material following the formation of a single or multiple-scab type fracture. For a given impact situation, there may be a fairly wide range of target thicknesses between the condition of the first tensile crack resulting from scabbing and the condition of complete structural breakdown resulting from scabbing or perforation of the target. However, some knowledge of the approximate target thickness at which the scabbing phenomenon begins to occur would give the space craft designer a better insight into the realm of target behavior intermediate between penetration without scabbing and perforation.

DISCUSSION OF THE MATERIAL PARAMETERS USED IN THIS STUDY

For given projectile and target geometry and impact conditions, target behavior is a function of the pertinent material properties that are operative under the prevailing impact conditions, which include high pressures, high strain rates and possible high or low ambient target temperatures. Since the fundamental material properties used in this study, of necessity, refer to conditions which are greatly different from those under hypervelocity impact loading, some justification or at least discussion of the adequacy of their use is required.

The projectile and target material properties presently being used in the study include densities under normal pressures and temperatures, and mechanical properties under static loading, with the exception of the dynamic tensile yield strength at relatively low strain rates. Also, with the exception of shear strength and Brinell hardness, all of the mechanical properties used are tensile properties.

While it is well known that material behavior changes radically under conditions of high pressure, high strain rate and large temperature changes, it is believed that the properties used in this study are, generally speaking, indicative of the behavior under conditions of high speed impact. That is, higher strain rates generally produce greater material strengths, greater rigidities and less ductility. Temperature decreases, in general, have similar effects on material strength,rigidity and ductility as strain rate increases. Also decreasing temperatures generally increase material hardness. With regard to high and low target temperatures, it appears that high ambient target temperatures, substantially below the melting point of the material, are probably not as important as low temperature effects, since material behavior at higher temperatures usually takes the form of a delayed creep or flow, which would not seem to be pronounced under very rapid transient loads. High pressures generally increase material strength, rigidity, ductility and hardness. The use, in a comparative manner, of the more accurately defined static and low strain rate material properties seems to be further justified in light of the knowledge that many factors such as thermal effects and modification of the crystalline structure of the target material by transient stress waves may have a decided influence on behavior, apart from the mechanical properties of the target material, and such factors as these are little understood or difficult to evaluate at present.

The following is a summary of the general effects of increased strain rates and pressures and decreased temperatures on material behavior:

	Increased Strain Rate	Decreased Temp.	Increased Press.
Strength (Generally)	Greater	Greater	Greater
Rigidity (Generally	Greater	Greater	Greater
Ductility (Generally)	Less	Less	Greater
Brinell Hardness	--	Greater	Greater

The Brinell definition of hardness is specified since hardness is defined in various ways, some of which may not follow this general behavior (for example, when defined as energy absorbing capacity).

The previous discussion has summarized a few of the more pertinent aspects of material behavior under conditions which, for low temperatures, probably approximate those found in the hypervelocity impact of a meteoric particle with a space vehicle. However, our experimental information on the effect of high strain rates and high pressures on fundamental material behavior falls far short of those experienced in hypervelocity impact loading. Also, it would be foolhardy not to expect that some contradictions to the above general rules exist.

For example, certain grades of mild steel are known to have a so-called "brittle range" under static loading (ordinary room temperature to about 500 degrees Fahrenheit) where an increase in temperature is accompanied by an <u>increase</u> in strength and brittleness. But this is abnormal when compared with other temperature ranges for the same material and is not found at all in most other metals.

Bjork[2] has pointed out an apparent inconsistency in relative material rigidity under high pressures as compared with low pressures, although it does not violate the general statement that rigidity increases with pressure. He showed that the hugoniots for some metals tend to "cross over". Specifically, the graphs of pressure versus relative density (ρ/ρ_0) for lead and aluminum cross. At low pressures aluminum is more resistant to density change than lead, but at high pressures this is reversed. While a theoretical study of the mechanics of impact behavior must necessarily consider the hugoniots, it is probable that in a statistical study this effect can be assumed to be reflected generally in the relative material densities, strengths, rigidities, etc. The important fact in this regard seems to be that the hugoniots for different materials have the same general shape.

EMPIRICAL MODELS

The experimental results from approximately 1000 shots by various investigators have been analyzed by the RPC 4000 digital computer and results are just beginning to appear. The first analysis considered penetration depth as the dependent variable and solved for the k_i in the equation

$$P_c = k_o \, v^{k_1} \rho_t^{k_2} \rho_p^{k_3} \, V_p^{k_4} \, T^{k_5} \, Y_t^{k_6} \, Y_p^{k_7} \, C_t^{k_8} \, U_t^{k_9} \, D_p^{k_{10}}$$

The independent variables were dropped one by one and the effect of the dropped variable on the k_i of the remaining variables was observed. The results of this analysis will be discussed in the next quarterly report.

In addition, various correlation coefficients between the log of the dependent variable (P_c) and the logs of the above independent variables were computed. No new or interesting results were obtained from the regular correlation coefficients. However, the multiple correlation coefficients, which measure the degree of association between the log of the dependent variable and the logs of any number of independent variables taken together, are of interest. The multiple correlation coefficients between log P_c and the logs of certain independent variables are summarized below.

Independent Variables	Multiple Correlation Coeff.
$v, \rho_t, \rho_p, V_p, T, Y_t, Y_p, C_t, U_t, D_p$	.9614
$v, \rho_t, \rho_p, V_p, T, Y_t, Y_p, C_t, U_t$	.9565
$v, \rho_t, \rho_p, V_p, T, Y_t, Y_p, C_t$	.9499
$v, \rho_t, \rho_p, V_p, T, Y_t, Y_p$	.9489
$v, \rho_t, \rho_p, V_p, T, Y_t$	.9454
$v, \rho_t, \rho_p, V_p, T$	.8746
v, ρ_t, ρ_p, V_p	.8703

The correlation coefficient between log penetration and the logs of the ten independent variables listed is about 0.96. This means that 96% of the variance in the log of the penetration is explained by the logs of these ten independent variables. Only 4% of the variance is not explained. Dropping the projectile diameter, target tensile strength, target dilatational wave velocity, and the projectile yield strength as independent variables still results in 94% of the variance in log P_c being explained. However, deletion of the target yield strength reduces the explained variance to 87%. Dropping the target temperature as an independent variable still leaves the explained variance at 87%. All of these correlation coefficients proved significant using the F distribution as a test.

The significance of the target yield strength above many of the other independent variables is quite startling, but it should be mentioned that a large number of the experimental shots were performed at impact velocities below 10,000 feet per second. Further discussion of these results will be postponed until the next quarterly report.

The model mentioned in the previous progress report, which expresses the target penetration in dimensionless form (P_c/D_p as dependent variable), has been analyzed by the computer, but sufficient time to interpret these results did not exist during this report period.

About six hundred additional experimental shots from other sources are now ready to be punched onto computer tapes. A second computer analysis on the combined data will be attempted during the next report period. Based on the analysis of the results from the above program, the models will be revised by adding some variables and dropping others. It is anticipated that the total number of experimental shots available after publication of the Fifth Hypervelocity Symposium Proceedings will approach two thousand. Unfortunately, shots at impact velocities above 20,000 feet per second are still quite scarce.

When all of the data available to date has been punched onto computer tapes, various impact velocity intervals will be considered separately as mentioned in the first quarterly report.

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2. Bjork, R. L., Third Symposium on Hypervelocity Impact VII (1959), p. 35

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